The Fundamental Plane of Black Hole Activity and the Census of the Local Black Holes' Population

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Abstract. Studying a sample of both strongly and weakly active galactic nuclei with measured masses and 5 GHz and 2-10 keV core luminosities, together with a few galactic black holes simultaneously observed in the radio and X-ray bands, Merloni, Heinz, & Di Matteo (2003) showed that the sources are correlated through a "fundamental plane" relationship in the three-dimensional $(\log L_{\rm R}, \log L_{\rm X}, \log M)$ space. Here I elaborate on how such a relationship can be used to infer directly mass and accretion rate of any black hole given its radio and X-ray fluxes, complementing the information obtained from optical/UV surveys. As an example, I show how the local X-ray and radio luminosity functions, coupled with the black hole mass function derived from the $M - \sigma$ relation, provide us with an accretion rate function. We found that the typical X-ray Eddington ratio of an active black hole at redshift zero is about 5×10^{-4}.

1. Introduction

In a recent paper Merloni, Heinz, & Di Matteo (2003) have shown that disc and jet emission from active black holes of any mass, from galactic X-ray binary sources to the most powerful quasars, are physically and observationally correlated phenomena. Their main result is the discovery of a "fundamental plane" of black hole activity; that is, if we define the instantaneous state of activity of a black hole of mass M (in units of solar masses), by the radio and hard X-ray luminosity of its compact core, and represent such an object as a point in the three-dimensional space $(\log L_{\rm R}, \log L_{\rm X}, \log M)$, all black holes (either of stellar mass or supermassive) will lie preferentially on a plane, described by the following equation:

$$\log L_{\rm R} = (0.60^{+0.11}_{-0.11}) \log L_{\rm X} + (0.78^{+0.11}_{-0.09}) \log M + 7.33^{+4.05}_{-4.07}. \quad (1)$$

There are two main reasons why such a long sought-after correlation has been discovered just now. The first is the importance of having large numbers of accurately measured black hole masses, which only became available in the *HST* era thanks to the exquisite spatial resolution needed for this kind of dynamical studies (see e.g. Magorrian et al. 1998). Moreover, the tight empirical correlation between black hole masses and central velocity dispersion of the host's bulge now allows to infer BH masses from larger scale galactic properties, greatly

increasing the number of reliable mass estimates available, at least in the local universe.

The second crucial factor is the identification of the hard (2-10 keV) X-ray spectral range as the best suited to unveil accretion activity, because of the little importance of absorption in that band (barred Compton thick sources, of course). However, the search for hard X-ray emission in all but the brightest galactic nuclei had to wait until the launch of the *Chandra* satellite before it could be carried on in a systematic fashion (see e.g. Ho et al 2001).

Although currently marred by a large intrinsic scatter (see the discussion in Merloni at al. 2003), the fundamental plane relationship opens the way to a number of potentially important applications in the study of large samples of black holes, not least because the physics behind it is reasonably well understood (Begelman, Blandford, & Rees 1984; Falcke & Biermann 1995; Merloni et al. 2003). Here I would like to point out a simple way of using the fundamental plane relation as a (gross) mass *and accretion rate* estimator. Coupling the two well determined local radio and X-ray luminosity functions of AGN through equation (1), it is possible to infer the main properties (mass and accretion rate) of the entire population of supermassive black holes (SMBH) in the local universe. Within the conference perspective, the goal of such an exercise is to highlight the importance of a multiwavelength approach to SMBH population studies. If large optical/UV surveys as SDSS are still crucial for determining BH masses (either directly or via the $M - \sigma$ relation), X-rays and radio data provide important clues on BH activity and physical state.

2.   Measuring Masses and Accretion Rates

Equation (1) can be inverted to relate BH masses to observed nuclear radio and X-ray fluxes and the distance D (in Mpc):

$$\log M \simeq 16.3 + \log D + 1.28(\log F_{\rm R} - 0.60 \log F_{\rm X}) \pm 1.06. \qquad (2)$$

This is an entirely empirical relation, and as such is model independent. On the other hand, it is also possible to relate the observed X-ray and radio luminosities to the second fundamental physical parameter that characterizes any active black hole: its accretion rate in units of Eddington luminosity, $\dot{m} \equiv \epsilon \dot{M} c^2 / L_{\rm Edd}$ (ϵ is the radiative efficiency). Such an inversion, however, is model dependent. The reader is referred to Merloni et al. (2003) for a thorough discussion on how to constrain disc-jet models on the basis of the observed correlation coefficients. There they showed that the fundamental plane is consistent with the most general theoretical relation between radio emission, mass and accretion rate expected from synchrotron emitting jets (regardless of their detailed geometrical and kinematical properties), provided that the X-ray emitting flow is radiatively inefficient. In this case, $L_{\rm X} \propto \dot{m}^{2.3}$, and the radio luminosity satisfies:

$$L_{\rm R} \propto \dot{m}^{1.38} M^{1.38} = \dot{M}^{1.38}, \qquad (3)$$

i.e., $L_{\rm R}$ scales with the *physical accretion rate* only.

Taken together, eqs. (2) and (3) can then be used to build a one to one map of the $L_{\rm R} - L_{\rm X}$ plane onto the $M - \dot{m}$ one, as shown in Figure 1.
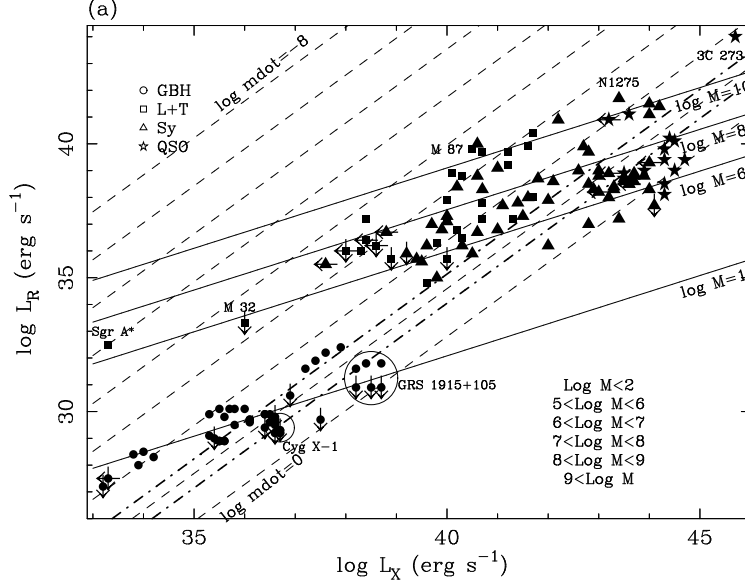
Figure 1.   The observed radio and X-ray core luminosity for the sample studied in Merloni et al. (2003). Superimposed are the lines of constant mass and accretion rate (in units of the Eddington luminosity, assuming a 10% efficiency). Dot-dashed lines bound the range of accretion rates where a mode change might take place between radiatively efficient and inefficient flows.

3.   The Census of Local Black Holes' Accretion Rate

The black hole mass function could be easily recovered if we knew the *conditional* radio/X-ray luminosity function $\Phi_C(\log L_X | \log L_R)$, namely the number of sources per unit volume with a given X-ray and radio luminosity:

$$\phi_M(\log M)\Delta \log M = \int_{(\log M,} \int_{\Delta \log M)} \Phi_C(\log L_X | \log L_R) d\log L_X d\log L_R, \quad (4)$$

where the double integral is performed over the range of radio and X-ray luminosities such that the logarithm of the mass derived from eq. (2) lies between $\log M$ and $\log M + \Delta \log M$. An analogous expression could be written down for the accretion rate function $\phi_{\dot{m}}$, in which equation (3) can be used to determine the area over which the integral must be performed.

While the Φ_C is not known, we do know the two separately determined X-ray and radio luminosity functions. Here I adopt for the 2-10 keV one, $\phi_X(\log L_X)$, that of Ueda et al. (2003), while for the 5 GHz one, $\phi_R(\log L_R)$, that determined at 1.4 GHz by Sadler et al (2002), assuming a radio spectral index of -0.7. Then I assume that it is possible to factorize the unknown conditional luminosity function as

$$\Phi_C(\log L_X | \log L_R) = \phi_X(\log L_X)\phi_R(\log L_R)f(\log L_X, \log L_R), \quad (5)$$

where f is a "matching" function that counts the number of object with X-ray and radio luminosities given by L_X and L_R, respectively. In such a way
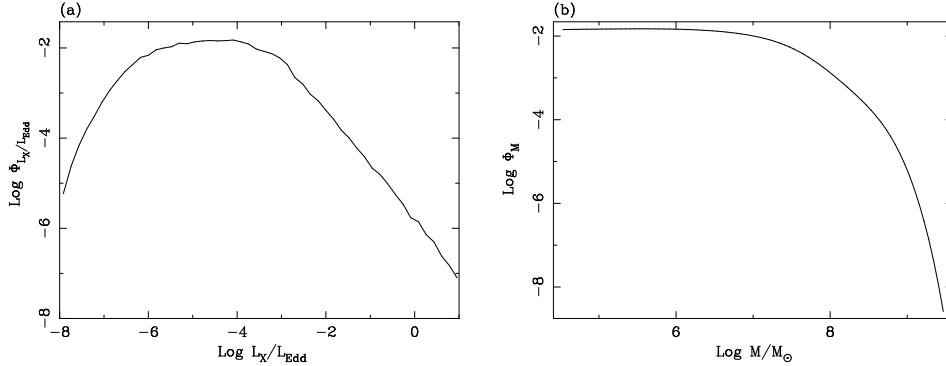
Figure 2.   Local accretion rate in Eddington units (panel a, estimated from the observed X-ray luminosity) and mass (panel b) functions for supermassive black holes in the nuclei of galaxies. The y axes show the number of sources per unit logarithmic interval per cubic Mpc.

our ignorance about the true conditional luminosity function is enclosed in the matching function f. A straightforward way around this obstacle is to use the local black hole mass function as determined from the $M - \sigma$ relationship (see e.g. Aller & Richstone 2002) to invert eq. (4), find the matching function f and use it to calculate the accretion rate function (more details in Merloni 2004, in preparation). In Figure 2, I show the result of such a calculation in the form of accretion rate and mass functions of local SMBH. As can be seen in Fig. 2a, the population of local black holes is dominated by sources shining, in the X-ray band, below 10^{-3} of the Eddington luminosity (assuming a 10% efficiency). This is in agreement what the average value found using the X-ray luminosity function of Seyfert 1 galaxies alone (Page 2001), or with theoretical estimates based on semianalitic Press-Schechter calculation of black hole growth in CDM universes (Haiman & Menou 2000).

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